A Review of Extra-Terrestrial Regolith Excavation Concepts and Prototypes

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ABSTRACT

Regolith is present on many extra-terrestrial bodies, and the crushed rock material it is made of contains many of the resources that are enabling for In-Situ Resource Utilization (ISRU). When extracted, these resources can be used to provide consumables such as rocket propellant, human life support, working fluids and gases for industrial processes and feedstocks for manufacturing. In addition, the regolith can also be very beneficial for construction purposes as an aggregate which can be used for construction materials and shielding for radiation protection and micrometeorite impact. Binders for regolith concrete may also be made from geopolymers that may be in the regolith. The regolith can be melted and drawn out into glass fibers and used as reinforcements in a metal, polymer, or concrete matrix. In addition, there is tremendous scientific and geological knowledge that can only be obtained by studying samples of the regolith.

However, none of these valuable activities can proceed without first acquiring the regolith granular material with some type of excavation device and method. Excavation is in the critical path of many workflows that will make up the capabilities required to establish a human and robotic presence in our solar system.

While scientific in-situ sampling of regolith in small quantities has been achieved since the dawn of the space age in the 1960’s, large scale excavation for mining and construction on extra-terrestrial bodies has only been contemplated, for many decades, but serious development and prototyping of excavation technologies for use in reduced gravity space environments was only started in the late 1990’s.

This paper will review and document the evolution of extra-terrestrial excavation concepts and prototypes based on the available literature and the personal experience of the author who has been working on regolith excavation technology development since 1998.

INTRODUCTION

Current NASA policy aims to use space resources on the Moon to ensure a sustainable future. On December 11, 2017, United States (US) space policy evolved with the signing of Space Policy Directive 1 which provides for a US led integrated program with private sector partners for a human return to the Moon followed by missions to Mars and beyond. Notably, it directs NASA to pursue human expansion

across the solar system (Hill, 2018). This goal will take many decades to achieve at the current rate of NASA human space missions but there is a way to accelerate such an effort, so that humanity and associated industry could expand to the asteroid belt and beyond in this century. Space resources and advanced technologies can be combined to create an affordable, rapid bootstrapping of space industry and solar system civilization (Metzger et al, 2013). The resources on the Moon are, to a large degree, contained in the photonic energy from the Sun, as well as minerals and volatiles in the lunar regolith. In order to acquire the regolith, robotic excavation technologies will be necessary, and these robotic excavators will be very different from terrestrial excavators. The reduced gravity and harsh environment on the Moon create unique excavation equipment requirements and there are severe mass and volume limitations that are imposed by the space transportation launch vehicles. Launching from the Earth's gravity well requires significant energy, so everything brought from Earth must be small and low mass, to avoid high costs and logistics burdens.

The NASA Artemis program is focused on landing humans at the South Pole of the Moon by the middle of the 2020's and the reason that the South Pole was chosen as the destination is that there is evidence of significant water ice deposits as well as other volatiles, while there are also regions of favorable solar illumination, which provides reduced thermal extremes and allows harvesting of solar energy on an almost continuous basis. These water and other volatiles including light hydrocarbons, sulfur-bearing species, and carbon dioxide, as well as mercury, magnesium, calcium, silver, and sodium were discovered by the NASA Lunar Crater Observation and Sensing Satellite (LCROSS) mission (Colaprete et al, 2010). While the geotechnical properties of the water and volatiles ices are unknown, there will be a need for acquiring these regolith resource feedstocks, and excavation is a candidate technology for doing so, which will be evaluated and compared to other competing technologies such as thermal mining. In thermal mining, ice is sublimated by applying heat directly to the surface and the near subsurface of the permanently shadowed region (PSR), the vapor is captured under a dome-like tent, then directed toward cold traps where it refreezes for transport to a processing system (Sowers et al, 2019).

If water ice cannot be found, then oxygen can still be extracted from the silicates contained in the regolith. At the lunar south pole these silicates are found in Anorthosite rock, an igneous rock characterized by its composition: mostly plagioclase feldspar (90–100%), with a minimal mafic component (0–10%). The plagioclase feldspar; is calcium-sodium alumino-silicate [(CaAl,NaSi)AlSi2O8] which can be found in the highlands granular rock materials that were crushed by high energy impacts from meteorites, comets and other space objects in the past 4.5 billion years. Excavation is required to acquire and deliver this regolith to an In-Situ Resource Utilization (ISRU) processing plant for oxygen extraction. Chemical engineering processes such as carbothermal reduction can be used to process and extract the oxygen.

REGOLITH ON THE MOON

While most lunar exploration architectures are focused on ISRU for propellant production, due to the large mass savings that can be achieved by avoiding the launch of propellant for the journey from the Moon back to Earth, there are many other uses of regolith which can be customers for lunar excavation providers. A list of some of the possible uses for regolith and volatiles derived resources is provided:

- Science investigations
- Geology investigations
- Propellant Oxidizer (O_2) Extraction from silicates
- Water Extraction (H_2O) for industrial consumables
- H_2/O_2 propellant
- Water (ice or liquid) radiation shielding
- Human life support consumables
- Plant growth consumables
- Fuel cell consumables
- Other volatiles extraction (He^3, H_2, CH_4, CO, etc.)
- Metals extraction for manufacturing
- Mineral glass fibers for manufacturing
- Regolith bulk aggregate (Berms, Contours, sandbags)
- Radiation bulk shielding for human health: Solar Particle Events (SPE) & Galactic Cosmic Rays (GCR)
- Nuclear power plant bulk regolith radiation shielding
- Construction materials feedstocks (Concrete, bricks, pavers, etc.)
- Industrial processes (solvents, reactant, etc.)
- Solar photo voltaic arrays manufacturing for electrical power
- Thermal wadi's for heat energy storage

The most critical regolith and volatiles related functions in these applications are regolith and ice excavation, transportation to the end user, delivery/emplacement and removal of tailings. Regolith excavation and transportation also plays a critical role in site preparation and construction. An example of the workflow associated with ISRU is shown in Figure 1.

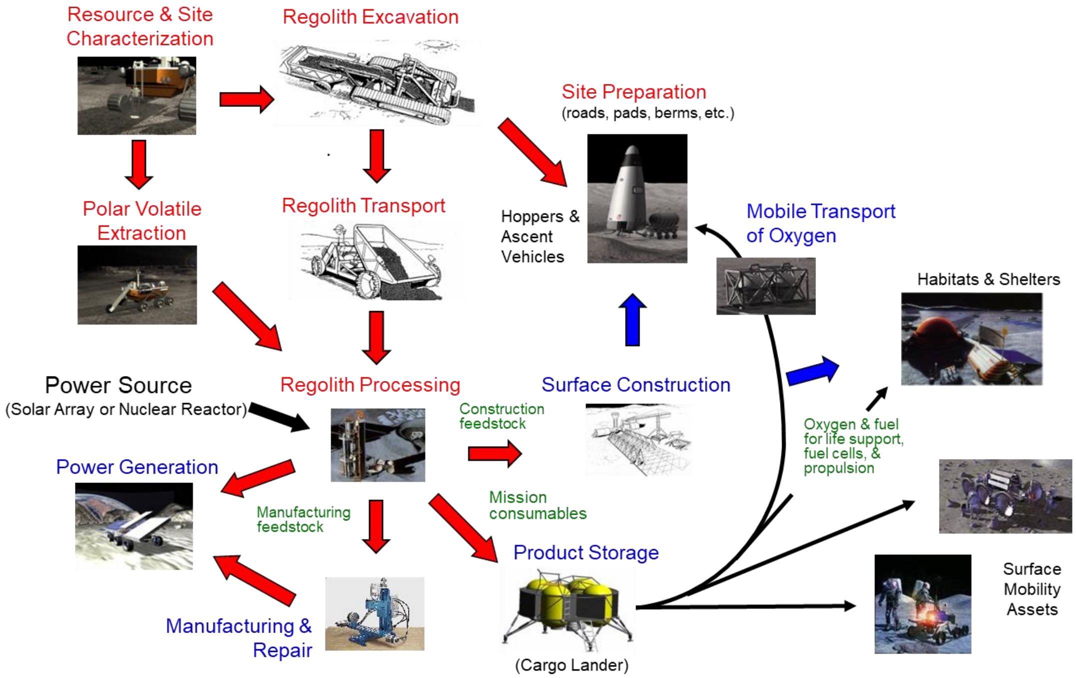

Figure 1. ISRU Workflow showing the Role of Regolith (G. Sanders, NASA)

Similar functions and workflows will also be necessary on Mars and at Asteroids, but the respective different environments will dictate bespoke solutions.

MINING REGOILITH

Regolith excavation and hauling is a large part of mining operations. On Earth the technology has evolved to include autonomous mining machines. The advantages of using autonomy include:

- Increased safety and improved working conditions for personnel
- Improved utilization by allowing continuous operation during shift changes
- Improved productivity through real-time monitoring and control of production loading and hauling processes
- Improved draw control through accurate execution of the production plan and collection of production data
- Lower maintenance costs through smooth operation of equipment and reduced damage
- Remote tele-operation of equipment in extreme environments
- Deeper mining operations with automated equipment
- Lower operation costs through reduced operating labor
- Reduced transportation and logistics costs for personnel at remote locations
- Control of multiple machines by one tele-operator human supervisor

Lessons learned from terrestrial mining can be applied to extra-terrestrial mining, but the machines themselves will be very different, and will require a high degree of innovation and technology development. Some of the distinguishing features are:

- Lunar excavation requirements are different than terrestrial excavation
- Launch mass and volume limitations
- Low reaction force excavation in reduced and micro-gravity
- Operating in regolith dust
- Fully autonomous operations
- Encountering unknown sub surface rock obstacles
- Unknown water ice / regolith composition and deep digging
- Operating in the dark cold traps of permanently shadowed craters
- Unknown soil mechanics in polar regions
- Extreme access and mobility
- Slopes >35 degrees
- Extended nighttime operation and power storage
- Electrical power storage with high power density
- Thermal management in temperature extremes
- Robust "line of sight" RF or laser communications
- Long life and reliability
- Long term maintenance & life cycle

Relevant technology development efforts have proceeded over the past 20 years, mostly for lunar regolith mining which can be extrapolated to Martian regolith mining. Asteroid regolith mining requires a completely different approach due to the very low 1/1000th G gravity field and the friable nature of the boulder and rubble piles found in asteroids. This paper will be limited to lunar excavation technologies and a future paper will address Martian and asteroid excavation for mining resources. Site preparation and construction are also a large customer for regolith excavation and transportation, but very little research has been performed in these domains, so this topic is also deferred to a future paper.

HISTORY OF LUNAR EXCAVATOR PROTOTYPES

The development of lunar regolith excavation robot prototypes was not seriously attempted until 2001, when Dr. Michael B. Duke, a former NASA geologist developed a bucket wheel excavator prototype with a team at the Colorado School of Mines (Muff et al, 2004) which is shown in Figure 2. Some testing was done using regolith simulants in collaboration with NORCAT in Sudbury, Canada (Boucher, 2004). The bucket wheel was then adapted by Larry Clark and Tim Muff, while working for Lockheed Martin inc., and transformed into a bucket drum with inherent digging, storage and dumping qualities (Clark et al, 2009). After ISRU field tests in an analog test site on Mauna Kea volcano in Hawaii revealed excavator traction issues, a variety of other designs were also attempted and tested in regolith simulant bins. The NASA Centennial Challenge for Lunar Regolith Excavation (Everingham et al, 2008, Comstock et al, 2009) created a large pool of different designs that were

tested from 2007-2009 in JSC-1A regolith simulant during the competition. The winning design was a bucket ladder style excavator which is advantageous for high speed mining but could have reliability issues due to the complexity of the mechanisms. While the competition only had a 30 minute run period, actual lunar operations will require years of operation, making reliability and repairability the primary concern. In 2010, the NASA Swamp Works team at Kennedy Space Center recognized that limited reaction force was the primary issue for lightweight lunar excavation, so they developed a counter-rotating bucket drum excavator which provides zero-horizontal reaction forces. Subsequent testing has shown this to be a very feasible design with good excavation results achieved during gravity offloading tests (Figure 4) in Black Point 1 (BP-1) lunar regolith simulant (Schuler et al, 2019).

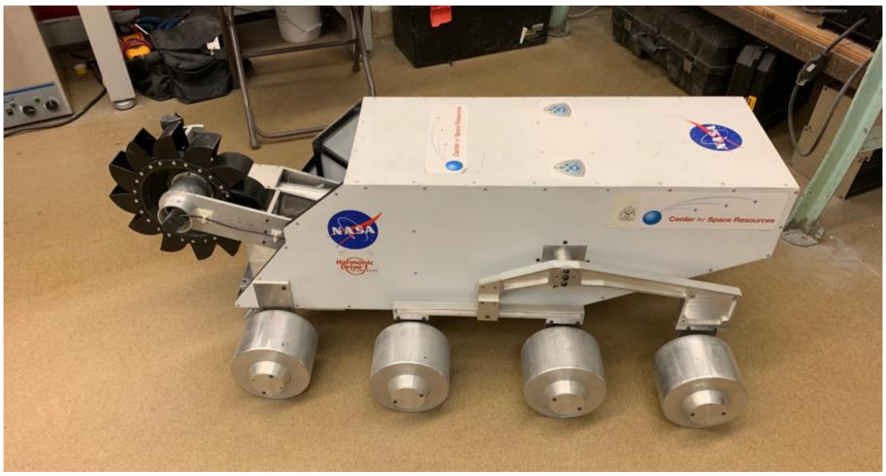

Figure 2. Colorado School of Mines Bucket Wheel Excavator

Other prototypes were tested during the NASA Desert Research & Technology Studies (RATS) analog field tests. In 2009-2011 a dozer blade was tested on a 1,000 kg lunar rover prototype called “Chariot” with good results (Mueller et al, 2009), The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robot from the Jet Propulsion Lab (JPL) demonstrated a bucket excavator mounted on two of its limbs, and an actuated boom mounted bucket from Glenn Research Center (GRC) and Kennedy Space Center (KSC) on a Johnson Space Center (JSC) Centaur rover was also tested (Johnson et al, 2012; Bauman, 2016). The Canadian Space Agency also funded field testing prototypes based on a Load-Haul-Dump (LHD) design using a vertical actuation mechanism similar to a forklift design, created by the Northern Centre for Advanced Technology (NORCAT), now known as Deltion, inc. The LHD implement was mounted on a Ontario Drive & Gear (ODG) inc. mobility platform developed with Neptec, inc. Test campaigns were completed in Canada and Hawai’i (Visscher et al, 2014).

Figure 3. NASA Chariot rover with a bulldozer blade attached to it during Desert RATS field tests on sand dunes in Moses Lake, Washington.

The NASA Lunabotics Regolith Mining Competition (RMC) held at KSC has provided over 50 excavator prototypes each year since 2010 (Mueller et al, 2021), providing a wide variety of design ideas. Other efforts funded by the NASA Small Business Innovative Research (SBIR) program produced notable prototypes including the application of pneumatic excavation on a micro-rover by Honeybee Robotics, inc. (Zacny et al, 2009) A list of extra-terrestrial robotic excavator prototypes is shown in Table 1. International projects for lunar excavation that are known, have been limited to documented Canadian and very recent Australian efforts, but more international efforts could exist and are not addressed in this paper.

Figure 4. NASA Regolith Advanced Surface Systems Operations Robot (RASSOR) excavator undergoing gravity off-loading tests

Table 1. History of NASA lunar excavator prototypes

Dates	Excavator Prototype
1989-91	NASA Space Exploration Initiative (SEI) Eagle Engineering inc. Concept Studies
2001-2011	Colorado School of Mines (Dr. Mike Duke research initiative)
2007	NASA GRC Cratos Scraper Excavator
2007-2009	NASA Centennial Challenge for Lunar Excavation
2008	Lockheed Martin Bucket Drum - Mauna Kea, Hawai'i NASA Field Tests
2008-2012	Canadian Space Agency, Mauna Kea, Hawai'i ISRU Tests (NORCAT[#] / Ontario, Drive & Gear (ODG) inc./Neptec inc. Juno Rover)
2009-2010	NASA KSC LANCE* Dozer blade & JSC Chariot Mobility Platform
2009-2011	JPL ATHLETE[†] hexapod robot with bucket implement
2009-2010	Caterpillar inc. Multi Terrain Loader Tele-Operations at JSC
2009-2010	SysRand inc. Moonraker bucket chain excavation implement
2009-2015	Honeybee inc. Pneumatic PlanetVac Micro Excavator
2010-2012	NASA JSC Space Exploration Vehicle (SEV) & LANCE
2010-2022	NASA Lunabotics Robotic Mining Competition
2010-2012	Honeybee inc. Planetary Volatile EXtractor (PVEX)
2010-2012	Astrobotic inc. Polaris Bucket transverse bucket wheel excavator
2013-2019	NASA JSC/GRC/KSC Centaur+ APEX^ + Badger bucket
2010-2019	NASA KSC Swamp Works RASSOR[ε]
2019-2022	NASA KSC Swamp Works ISRU Pilot Excavator (IPEx)

[#] Northern Centre for Advanced Technology (NORCAT) now Deltion, inc.
* Lunar Attachment Node for Construction Excavation (LANCE)
[†] All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE)
^ Advanced Planetary Excavator (APEX)
[ε] Regolith Advanced Surface Systems Operations Robot (RASSOR)

TAXONOMY OF LUNAR REGOLITH EXCAVATOR DESIGNS

During the last 23 years, many excavator designs have been prototyped, primarily for competitions. The rules of these competitions reward fast results with excavation rates as high as 1,000 kg/hour having been demonstrated. Actual missions to the Moon will reward reliability and there will be more time to excavate, so that the design criteria will be different. Nevertheless, a large variety of robotic excavator designs have been proposed and prototyped which can inform future design efforts. The taxonomy of these designs, based on the NASA Lunabotics Robotic Mining Competition entries by university teams, has been cataloged (Mueller et al, 2021) and is shown in Tables 2, 3 & 4.

Table 2. Most popular excavation and regolith transportation mechanisms

	regolith		regolith
# sys	**excavation mechanism**	# sys	**transportation mechanism**
101	bucket ladder	103	bucketladder
37	front end loader	40	in scoop
29	bucket belt	22	conveyor belt
27	bucketwheel	21	bucketbelt
17	bucket drum	15	auger
15	snow blower (auger or brush)	11	Over shoulder dump into hopper
12	auger	8	chute for guiding regolith
8	backhoe	7	bucketdrum
8	bulldozer	7	drum
8	scraper	6	bucketwheel
7	large single scoop	6	impeller
4	dual auger	4	bucket rim
4	dual bucket wheel	4	bucketwheel discharge through bottom
4	rotating brush	4	in bucket
3	excavating wheels	4	rotate scoop to slide simulant in hopper
2	claw/gripper scoop	3	throw from impeller
2	dual bucketladder	2	bucketwheel with side discharge
2	dual counter rotating bucketdrums	2	paddle conveyor
2	large bulldozer scoop	2	raising scraper with chute
2	paddle conveyor	2	thrown from brush up ramp

Table 3. Most popular regolith storage and regolith dumping mechanisms

	regolith		regolith
# sys	**storage mechanism**	# sys	**dumping mechanism**
213	hopper	111	rotating tilting hopper
41	in scoop	36	conveyor belt as bottom and inclined side c
10	drum	30	scoop tilting
6	bucketdrum	7	auger
6	on conveyor belt	6	counter rotate buckedrum
4	auger	6	raising/tilting hopper/ scissor lift
3	scraper	5	conveyor belt
2	in bucket	5	fixed rotating hopper
1	bucketdrums	4	raising hopper with back chute
1	bucketladder	4	rotate and lift scoop to slide off back into co
1	bulldozer	4	scissor lift and tilting hopper
1	drums	4	tilted raised drum
1	in auger pipe	3	bucketladder
1	in clamshell	3	raising counterrotating drum
1	inside tube body	3	raising hopper with bottom conveyor belt
1	large conveyor belt with crazy carpet	3	tilting raising scoop
1	saddle hopper (two sides)	3	tilting scoop
1	scraper scoop	2	angled vibrating hopper
1	side hopper	2	chute
1	slide	2	horizontal conveyor belt

Table 4. Most popular robot movement mechanisms

# sys	robot movement mechanism
173	4 fixed wheels
73	tracks
21	6 fixed wheels
10	4 steerable wheels with custom profile
6	two auger drums to propel
5	stationary with swivel
4	4 fixed track wheels
3	4 digging wheels
2	3 wheels (2 driven, one steering)
2	4 six-legged wheels
2	4 wheels with suspension
2	each of two robots hase 4 fixed wheels with grousers
2	four individual steerable tracks
2	three robots working together, two transport, one excavator, each with 4 fixed wheels
1	3 fixed wheels (front wheel swivels freely)
1	3 large wheels (2 with grousers, third with scoops)
1	4 medium and 2 large front wheels
1	4 wheels (two steerable coupled) with grousers
1	4 wheels with grousers, two of which have buckets to fill with regolith to increase counterweight
1	4 wheels, of which 2 steerable rear wheels

CONCLUSIONS

Regolith excavation and transportation form the basis of regolith mining and also have critical applications in site preparation and construction activities. The unique extra-terrestrial environments (Moon, Mars, Asteroids) where excavation for ISRU and construction are likely to be needed are so different from terrestrial environments that completely new methods and devices must be invented and developed to meet these future needs. Logistics and space transportation are also difficult and expensive, so reducing mass and volume are important considerations for excavation equipment.

Since 2001, many robotic excavator prototypes for extra-terrestrial uses have been attempted. However, the fidelity of the testing environments remains at a low technology readiness level (TRL) of 3 or 4, and the reliability of the proposed designs has not been demonstrated. Since these excavation robots will be operating in a much harsher and regolith interactive manner than current Mars and Moon scientific rovers, new ways of dealing with regolith dust, rocks, cryogenic icy regolith, extreme terrain, very cold operating temperatures, lunar nights, shadowed regions and more must be developed, before the NASA Artemis program, and others, can successfully use ISRU and perform in-situ construction.

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